Use of Multiple Criteria Decision Analysis in the Marine Corps Advanced Amphibious Assault Vehicle (AAAV) Program

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Abstract

Multiple Criteria Decision Analysis (MCDA) was an integral part of concept definition for the Marine Corps AAAV program. Three levels of trade studies were performed: (1) whole system trades, (2) subsystem/component trades, and (3) concept selection trades. Whole system trades determined the "best" balance of AAAV "core capability" performance requirements, cost, and weight. Subsystem/component level trades selected specific technologies to meet the performance requirements defined for each "core capability" in the whole system trades. Concept selection trades were used to select the "best" AAAV alternatives(s).

Whole system trades began with a mission area analysis that included definition of threat, user/source requirements, and operational & organizational concept(s). Low, moderate, and high target performance levels were then identified for system "core capabilities". Using a Design of Experiments (DOE) approach, functional relationships between the "core capability" target performance level requirements and combat effectiveness, cost, and weight were developed for use in a Multi Criteria Mathematical Programming (MCMP) model. The MCMP model was used to generate a set of non-dominated candidates that were then evaluated using MCDA to select the "best" alternative(s) as defined by "core capability" performance levels.

Subsystem/component trades were conducted based on the "core capability" performance level requirements selected in the whole system trades. Each "core capability's" level helped further expand/focus its technology search and evaluation criteria.

The set of candidates, now defined by real technologies, was then evaluated using MCDA to select the "best" AAAV alternative(s).

This paper will describe the analysis process used for the AAAV whole system, subsystem/component, and concept selection trades.

Introduction

The AAAV is part of the Operational Maneuver From The Sea triad of vehicles which includes the Marine Corps' MV-22

Osprey tilt-rotor aircraft and the Navy's Landing Craft Air Cushion (LCAC). Its mission is to provide high-speed transport of embarked Marine Infantry from ships located beyond the horizon to inland objectives. General Dynamics is the prime contractor for the AAAV.

The AAAV will provide the Marine Corps a weapons system fully capable of implementing ship-to-objective maneuver as an integral part of the Amphibious Triad (AAAV, MV-22, LCAC) to execute the concepts of Operational Maneuver From the Sea (OMFTS) and Ship to Objective Maneuver (STOM).

Battlespace dominance by Marine Forces will be significantly enhanced as a result of the AAAV's high water speed and superior land mobility which have historically limited the rapid maneuver of armored combat vehicles. The AAAV is designed to allow immediate, high-speed maneuver of Marine Infantry Units as they emerge from attack positions aboard ships located beyond the visual horizon -- 25 miles and beyond. Projection of these forces will be conducted as a single, seamless stroke that capitalizes on the intervening sea and land terrain to achieve surprise and rapidly exploit weak points in enemy Littoral Defenses.

Contractual Requirement

The AAAV Dem/Val Request for Proposal and Statement of Work described the whole system trade study as follows:

"The contractor shall conduct total system core capability cost versus performance trade-off analyses of its AAAV(P) and AAAV(C) designs in order to determine optimum system performance and combat effectiveness relative to total system cost and weight to include procurement and operations and support costs. These trade studies shall include varying levels of capability in each of the core areas of lift, high water speed, land mobility, firepower, and survivability. The studies shall include levels of capability that are below required threshold values, values in the threshold to objective ranges, and values above the objectives. At least three levels of capability shall be studied in each of the core areas. The contractor shall employ the use of computer based combat effectiveness models, similar to the U.S. Army's 'Groundwars' or 'Combined Arms and Support Task Force Evaluation Model (CASTFOREM)' models, in order to determine overall system effectiveness of each of the combinations of capability. The results of these studies shall show clearly the effect of varying core capabilities against total system cost and weight."

The Role of Trade Studies in Systems Engineering

Trade studies are performed throughout product development as an essential part of the systems engineering process. The trade study process is controlled by systems engineering to ensure integration and balance all design requirements. Under the guiding principles of acquisition reform, trade studies must also include emphasis on cost versus requirements.

Trade studies are used to solve any complex problem where there is more than one selection criterion or multiple solutions, and provide documented decision rationale. These analyses are equally necessary for establishing system configurations and for accomplishing detailed design of individual components.

Trade studies provide a methodology for making informed decisions that can be backed up. Trade studies justify and document important design decisions.

The scope of a trade studies should be commensurate with the cost, schedule, performance, risk, and visibility associated with the decisions supported. Decisions with broad impact and visibility need better justification and documentation than decisions with limited impact.

The role of trade studies evolves with the phases of the acquisition process. During the Concept Exploration and the Program Definition and Risk Reduction phases, trade studies are used to establish the system configuration. During Engineering and Manufacturing Development, trade studies are employed to assist in selecting component/part designs. Later, as the system enters the Production phase, trade studies support make-or-buy, process, rate, and location decisions as well as examination of all proposed design changes.

Figure 1 shows where trade studies fit in the systems engineering process. The process begins with a validated need and continues through function allocation and synthesis. After the system is fielded, trade studies are used to identify potential product improvement actions to address product deficiencies.

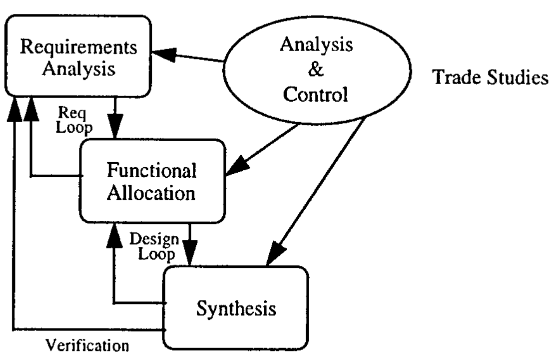


Figure 1. *Trade Studies are Integral to all Phases of the Systems Engineering Process.*

Fundamental Methodology

Methods for performing trade studies must allow for evaluating complex alternatives in the presence of multiple, conflicting, and incommensurate objectives. The key components of trade studies are the following:

- Decision criteria, i.e., a set of goals that characterize what makes a specific alternative desirable.
- A set of feasible alternative solutions.
- A measure characterizing how well the various solutions satisfy each of the decision criteria.
- Relative importance of each of the decision criteria in the selection process.
- A transformation of disparate measure units to common units.

These components are used to form a structured assessment of the suitability of each alternative as the solution to a problem. When this process is performed correctly, the alternative with the best assessment record will be the "best" overall solution.

The fundamental structure of a trade study is the goals hierarchy illustrated in Figure 2. This hierarchy contains all of the key components of any trade study methodology.

The goals hierarchy constitutes a MCDA model. The goals hierarchy begins with several fundamental goals as main branches. Each fundamental goal is then expanded and explained with more specific sub-goals and ultimately measures. The parameters of the model are the measurable sub-goals relative importance weights, W_i , the measure levels, ML_{ij} , for each of the measures "i" for each solution alternative "j", and the results of the transformation of measure levels to common units of utility, CU_{ij}. The transformation of measure levels to common units of utility,

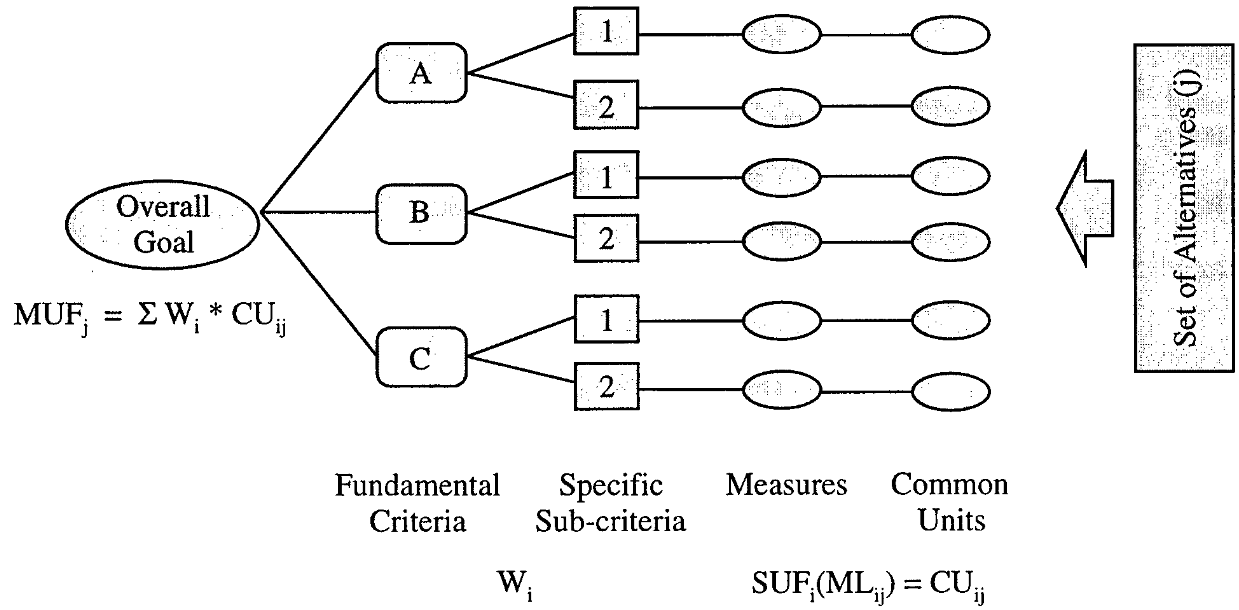


Figure 2. *The Goals Hierarchy is the Trade Study Model*

CU_{ij} , is accomplished by a "Single-measure Utility Function" (SUF_i). The model computation provides a score for each solution alternative given by the equation:

$$MUF_j = \sum_{i=1}^{n} W_i * SUF_i(ML_{ij}), \quad j = 1,m$$

where MUF is the "Multi-measure Utility Function" of an alternative.

The measurable sub-goals relative importance weights and transformation of disparate measure units to common units are judgmental data elicited from Subject Matter Experts (SMEs). Since these data are judgmental, it is essential that the sensitivity of the results to these data be assessed explicitly. If the ranking of alternatives is sufficiently insensitive to the judgmental data, then the solution is said to be robust.

The major benefits gained from conducting a trade study are insights into how the solution alternatives differ from one another and which alternative best meets the needs of a program. The use of numbers to quantify subjective values and relative importance weights simply enables the quantitative analysis. The real power of the quantitative analysis is the generation of qualitative insights through which decision makers can select the preferred alternative.

AAAV Trade Study Process

The fundamental methodology was converted into a standardized AAAV Trade Study Process as shown in figure 3. The standardized process was a series of four tasks composed of a total of ten steps.

The first task, STRUCTURE, defines the trade study model and solution alternatives.

The second task, DESCRIBE, provides quantitative and qualitative definition of the solution alternatives in terms of the model structure.

During the third task, CLARIFY, the trade

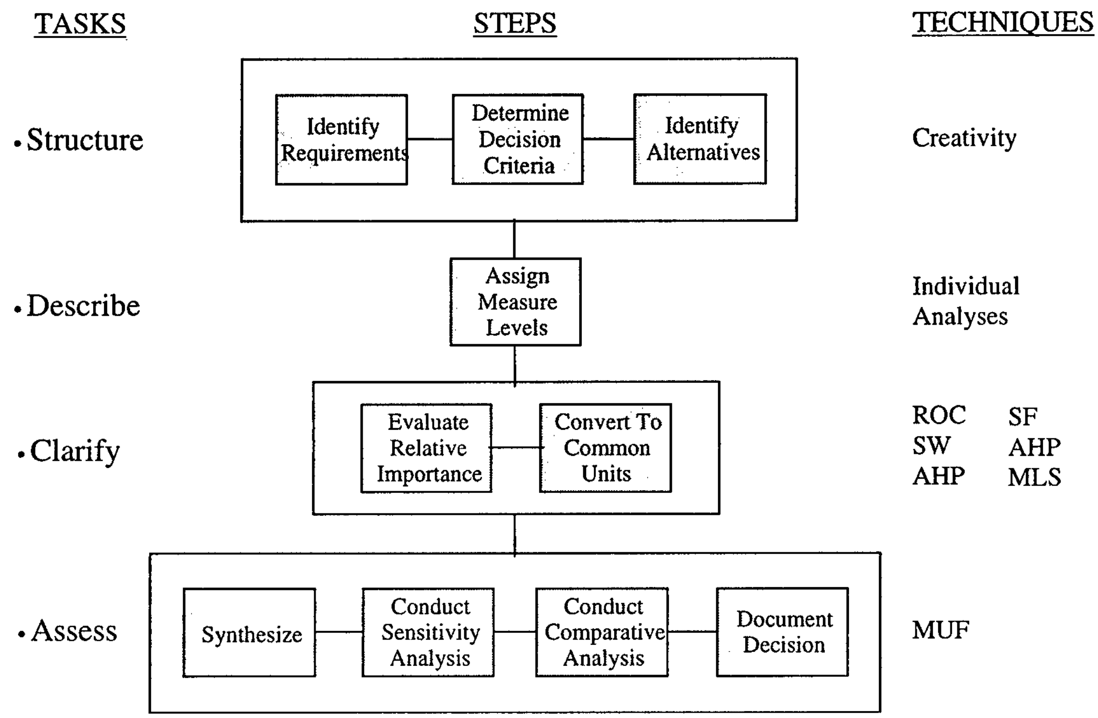


Figure 3. *Each Trade Study was Conducted Using the Standardized AAAV Trade Study Process.*

study model is populated with the judgmental data needed to differentiate between the solution alternatives. This is where the separation of objective and subjective elements comes in. Identifying the measure levels for an alternative is an objective process, while specifying relative importance of criteria and converting to levels of desirability is inherently subjective.

The fourth task, ASSESS, is the analysis leading to selection of the preferred solution alternative. It is accomplished by a ranking process that uses an additive scoring model. This additive scoring model uses all of the data generated during the previous steps.

Since much of the data is judgmental in nature, it is essential that the sensitivity of the results to these data be assessed explicitly. If the ranking of alternatives is sufficiently insensitive to the input data, then the solution is said to be robust.

Integration of Trade Study Levels

The AAAV concept definition methodology encompassed three levels of trade studies:

(1) Whole system level trades that resulted in definition of top level vehicle concepts defined by the "best" balance of AAAV "core capability" (High, Moderate, Low) performance requirements, cost, and weight,

(2) Subsystem/component level trades that resulted in selection of specific technology options to meet the performance requirements, cost, and weight levels defined for each "core capability" in the whole system level trades,

(3) Final concept selection from among a set of non-dominated vehicle solution alternatives brought forward from the entire set of subsystem level trades.

Figure 4 is a schematic of the integration of these three trade study levels. This figure will be followed closely in the discussions below. Each element will be explained in the context of the AAAV analysis.

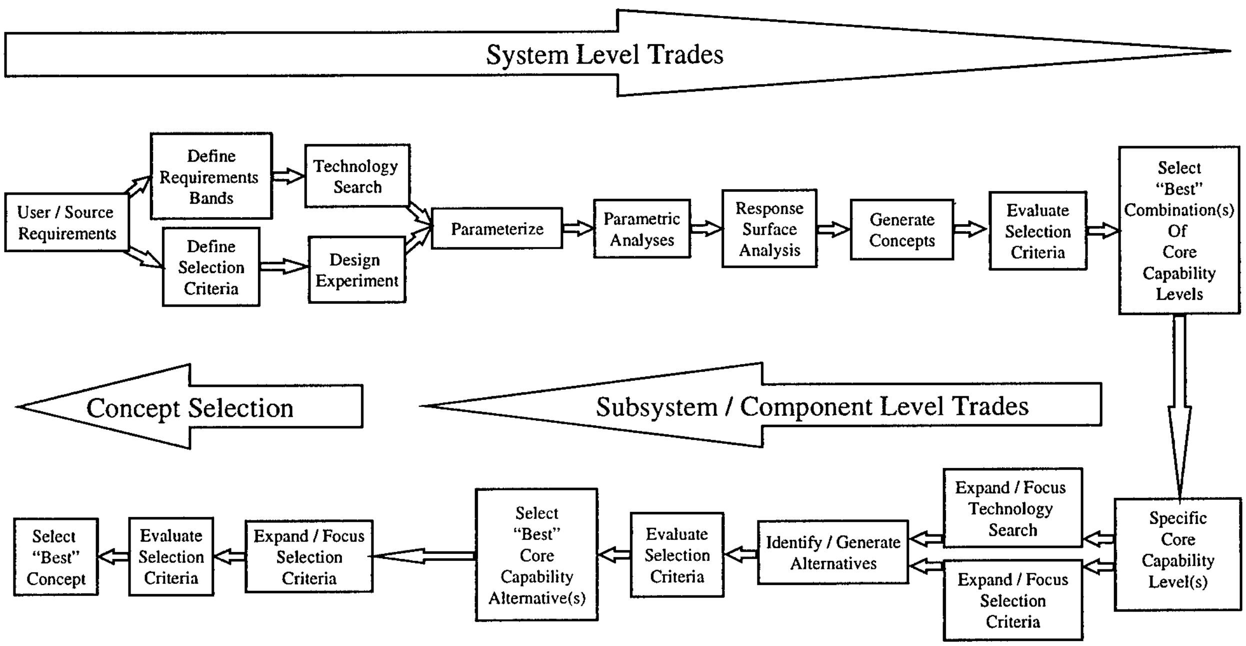
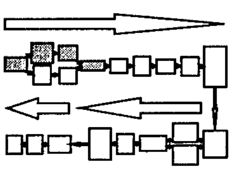


Figure 4. *The AAAV Concept Definition Methodology Integrated Three Levels of Trade Study.*

(1) Whole System Level Trades:



The whole system level trades began with an analysis of the basic user/source requirements for the five core capability areas of high water speed, lift, land mobility, survivability, and lethality. Specific capabilities within the five core areas of capability were identified together with their associated performance threshold and objective values. The threshold and objective values defined requirements bands that were the basis for a technology search that led to parameterization of high, moderate, and low requirements levels corresponding to below required threshold values, values in the threshold to objective ranges, and values above the objectives as shown in figure 5.

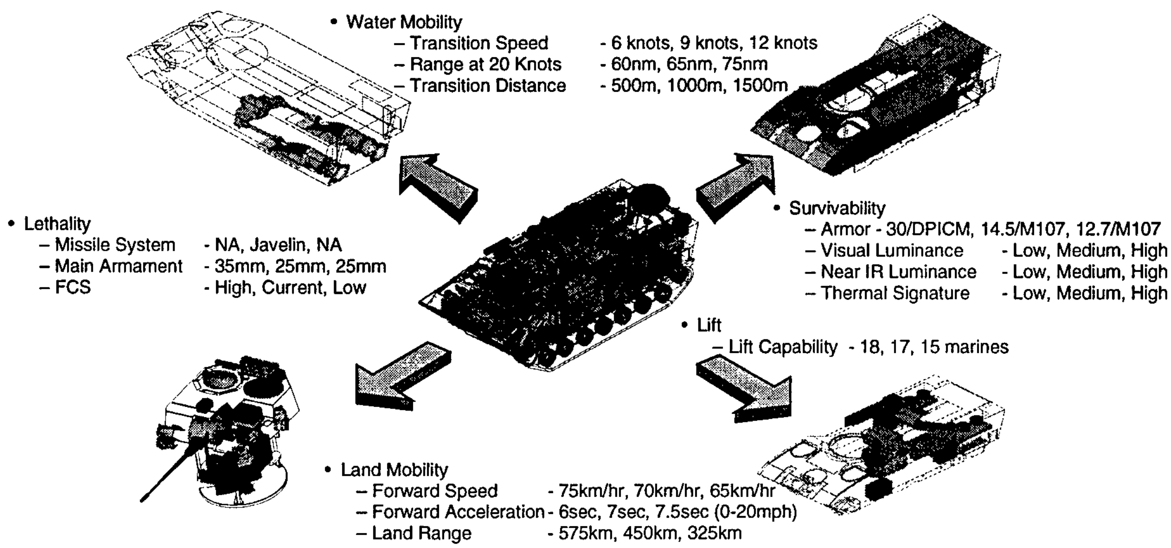
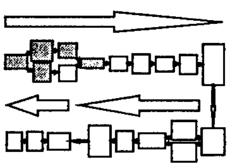


Figure 5. *Requirements were Parameterized to High, Moderate, and Low Levels for Specific Capabilities within the Five Core Areas of Capability.*



Criteria by which to evaluate the solution alternatives were then identified by further analysis of the user/source requirements. For AAAV, the fundamental criteria were cost, performance, and weight. Cost and weight needed no further breakdown into sub-criteria because they could be measured directly. Performance, on the other hand, needed further definition. The contractual requirement to conduct whole system trades clearly indicated that at the system level, combat effectiveness should be the prime measure of performance.

The CASTFOREM combat model was selected for conducting combat effectiveness assessments in two amphibious scenarios; a Northeast Asian (NEA) and a Southwest Asian (SWA) scenario using the expected enemy capability for the 2015 time frame. Four measures of effectiveness (MOE) were chosen for evaluation of the AAAV in these scenarios:

1. % Blue personnel casualties
2. % Blue AAAV surviving
3. % Red personnel casualties
4. % Red vehicle losses

The Automated Cost Estimator (ACEIT) and Pro/PDM in conjunction with Microsoft® Excel™ were selected for cost and weight modeling, respectively.

The four MOEs from the CASTFOREM combat model were aggregated into a MUF to simplify the analysis. A group of Marine Corps operational SMEs was selected and relative importance weights and SUFs for the four MOEs were elicited. The goals hierarchy for the whole system level trades with The SME assessed MOE relative importance weights and SUFs is shown in figure 6.

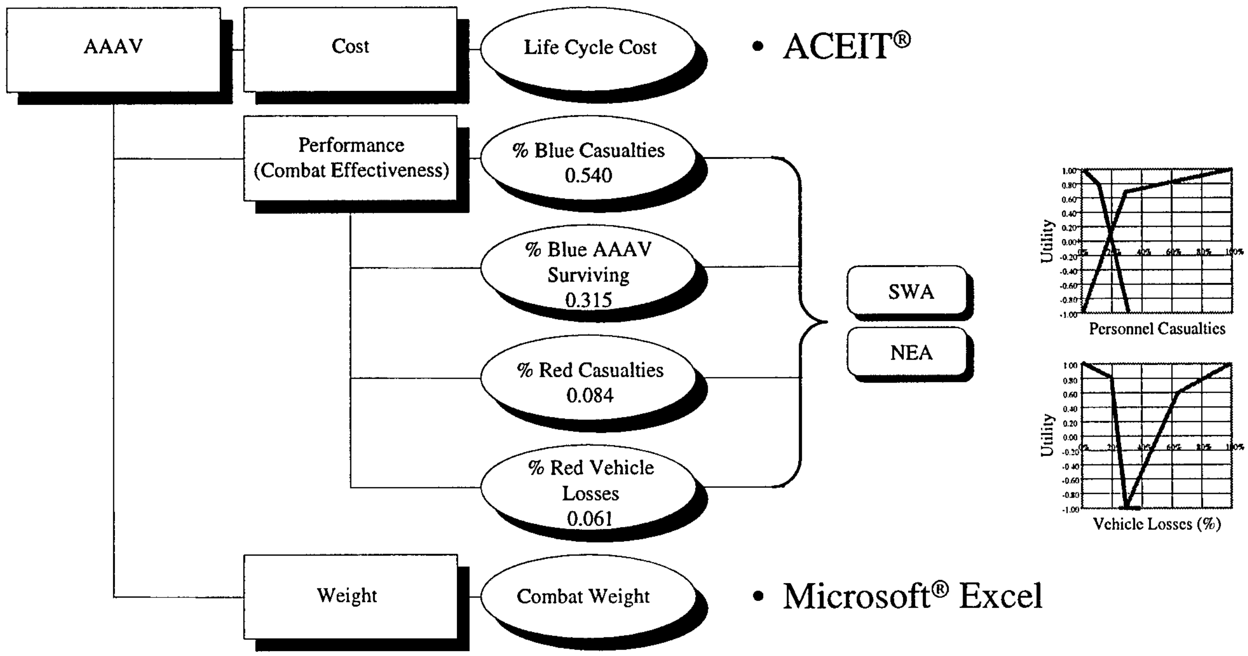
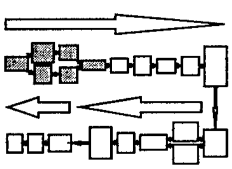


Figure 6. *The Goals Hierarchy for the Whole System Level Trades Included Cost, Performance and Weight Considerations*



The initial steps of the whole system trades, resulted in definition of requirements bands. Those requirements bands implied broad technology categories of interest and an associated parameterization of high, moderate, and low requirements levels for each of the specific capabilities within the five core capability areas. If all combinations of the parameterization were feasible, there would be $3^{12} = 531{,}441$ possible combinations of parameter levels which implies 531,441 different AAAV options to evaluate.

The ideal would be to evaluate all 531,441 possible AAAV options. Limitations on resources (computers, time, money, etc.) obviously precluded any such full evaluation. The standard approach to handling such a large task is to perform experiments with a representative sample of possible alternative solutions, and use these to estimate the expected results for all alternative solutions. This process is called Design of Experiments (DOE).

The AAAV DOE philosophy was to use a modification of the standard Face Centered Cubic design. The Face Centered Cubic design is a standard three-level fractional factorial experiment suitable for exploration of quadratic response surfaces. A Face Centered Cubic design consists of a three-level factorial "box" augmented by an experiment at the center point and symmetrically located "star" points. The central box is a full factorial design for 2 through 4 factors, and a half factorial design for 5 or more factors. The central factorial design spans the rectangular region of interest defined by the high, moderate, and low limits on the factor values. The "star" points lie on lines from the center point to the centers of the faces of the three-level

factorial box. The "star" points lie on the boundary of the region of interest. Figure 7 shows the experimental points for an experiment with three factors.

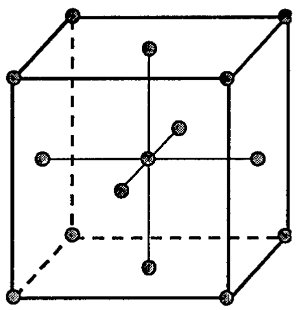
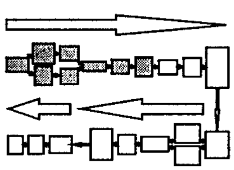


Figure 7. *Face Centered Cubic Design for a Three Factor Experiment.*



The DOE defined analysis run matrices for parametric use of the various models. The objective of the DOE and its implementation in the parametric analyses was to generate sufficient information about the interaction of different core capability levels with respect to the selection criteria to statistically derive relationships that could be used to infer selection criteria evaluation results for combinations of core capability levels that had not been run in the various models. These relationships are called response surfaces and they serve as "meta-models" of the various models within the range of parameters that had been run.

The index sets "A" and "S_A" were then defined as follows:

A = Set of core capability areas = {Water Mobility, Lift, Land Mobility, Survivability, Lethality}

and

S_A = Set of specific capabilities within in each core capability area in the set A.

Using these index sets, the variable X_{AS_A} was defined to represent a specific capability within a given core capability area. For example:

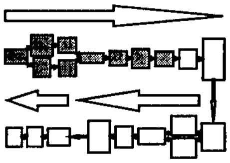
$$X_{41} \Rightarrow \text{Survivability - Armor}$$

With this representation, the quadratic response surfaces generated by the Face Centered Cubic experimental design for the three fundamental selection criteria are given by the regression equations:

$$\text{Performance} = p_0 + \sum_{A}\sum_{S_A} p_{AS_A} X_{AS_A} + \sum_{A}\sum_{S_A}\sum_{A'}\sum_{S'_{A'}} p_{AS_A A'S'_{A'}} X_{AS_A} X_{A'S'_{A'}} + \sum_{A}\sum_{S_A} p_{AS_A AS_A} X^2_{AS_A AS_A}$$

$$\text{Cost} = c_0 + \sum_{A}\sum_{S_A} c_{AS_A} X_{AS_A} + \sum_{A}\sum_{S_A}\sum_{A'}\sum_{S'_{A'}} c_{AS_A A'S'_{A'}} X_{AS_A} X_{A'S'_{A'}} + \sum_{A}\sum_{S_A} c_{AS_A AS_A} X^2_{AS_A AS_A}$$

$$\text{Weight} = w_0 + \sum_{A}\sum_{S_A} w_{AS_A} X_{AS_A} + \sum_{A}\sum_{S_A}\sum_{A'}\sum_{S'_{A'}} w_{AS_A A'S'_{A'}} X_{AS_A} X_{A'S'_{A'}} + \sum_{A}\sum_{S_A} w_{AS_A AS_A} X^2_{AS_A AS_A}$$

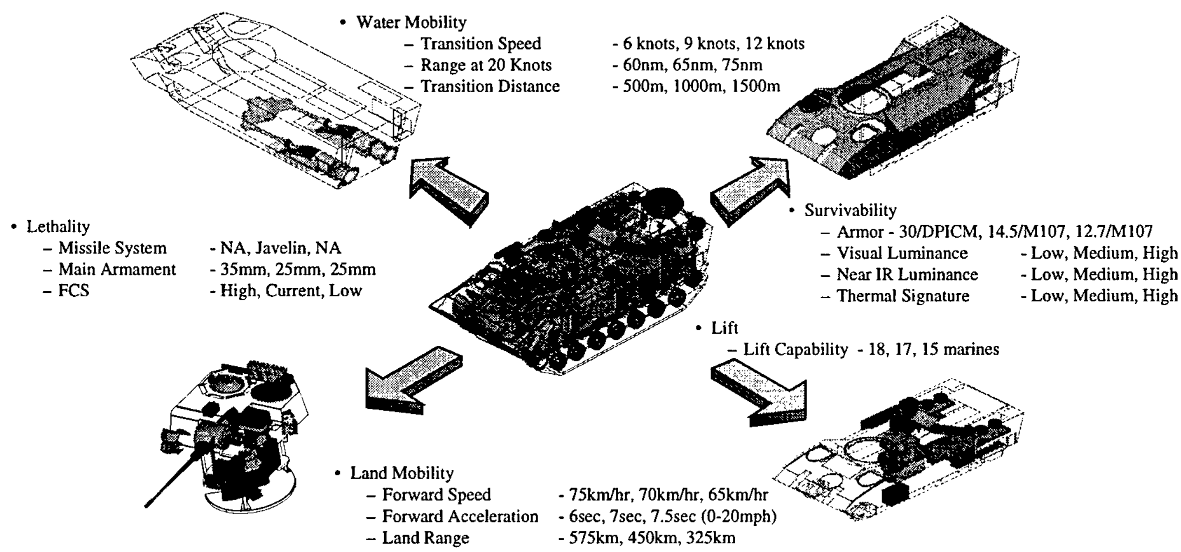


The selection criteria response surfaces for performance, cost and weight became the objective functions of a MCMP model that was used to generate a set of non-dominated candidate alternatives.

A solution is non-dominated if there is no other solution that is equal to or better than it in all three response factors, i.e., performance, cost and weight. The set of all non-dominated solutions is called the efficient frontier.

Figure 8 is a generic, non-technical description of the model. Technically, the model is a multi-criteria, nonlinear, 0-1 integer programming model. The model was solved using a standard MCMP solution procedure in conjunction with the "Solver" add-in to Excel. The solution procedure was used to generate a representative portion of the efficient frontier. The alternative solutions on this portion of the efficient frontier represented true trade-offs that were evaluated with a MCDA model to select a preferred alternative solution.

Select the Combination
of Technology Levels for Each Specific Capability
(High, Moderate, Low)



That

Maximizes Performance
Minimizes Cost
and
Minimizes Weight

While Adhering to Design Constraints That Require

Using Only Feasible Combinations of Technology Levels
Meeting Performance Threshold Requirements
Staying Within Cost and Weight Upper Bounds

Figure 8. *The MCMP is used to Generate a Representative Portion of the Efficient Frontier of Alternative Solutions.*

In order to specify the general mathematical model, the additional index set "I" was defined to be the set of specific technology levels, and the variable X_{AS_A} was extended to $X_{AS_A I}$ in order to represent the set of 40 0-1 variables corresponding to each specific capability technology level. The general MCMP model is then given by:

- Index Sets

A = Set of core capability areas = {Water Mobility, Lift, Land Mobility, Survivability, Lethality}

S_A = Set of specific capabilities within each core capability area in the set A.

I = Set of technology levels within each capability S_A = {High, Moderate, Low}

- 0-1 Decision Variables

$$X_{AS_A I} = \begin{cases} 1 & \text{if technology level "} i \in I \text{" is selected for specific capability } S_A \text{ in } A \\ 0 & \text{otherwise} \end{cases}$$

- Objective Functions

$$\text{Maximize Performance} = p_0 + \sum_A \sum_{S_A} p_{AS_A} \sum_I X_{AS_A I} + \sum_A \sum_{S_A} \sum_{A'} \sum_{S'_{A'}} p_{AS_A A'S'_{A'}} \sum_I \sum_{I'} X_{AS_A I} X_{A'S'_{A'} I'} + \sum_A \sum_{S_A} p_{AS_A AS_A} \sum_I X^2_{AS_A I}$$

$$\text{Minimize Cost} = c_0 + \sum_A \sum_{S_A} c_{AS_A} \sum_I X_{AS_A I} + \sum_A \sum_{S_A} \sum_{A'} \sum_{S'_{A'}} c_{AS_A A'S'_{A'}} \sum_I \sum_{I'} X_{AS_A I} X_{A'S'_{A'} I'} + \sum_A \sum_{S_A} c_{AS_A AS_A} \sum_I X^2_{AS_A I}$$

$$\text{Minimize Weight} = w_0 + \sum_A \sum_{S_A} w_{AS_A} \sum_I X_{AS_A I} + \sum_A \sum_{S_A} \sum_{A'} \sum_{S'_{A'}} w_{AS_A A'S'_{A'}} \sum_I \sum_{I'} X_{AS_A I} X_{A'S'_{A'} I'} + \sum_A \sum_{S_A} w_{AS_A AS_A} \sum_I X^2_{AS_A I}$$

- Constraints

– One technology level per specific capability

$$\sum_I X_{AS_A I} = 1 \quad \forall \text{ A and } S_A$$

– Feasible combinations of technology levels

$$\sum_A \sum_{S_A} \sum_I X_{AS_A I} = k \qquad \text{must have "k" of the technologies}$$

$$\sum_A \sum_{S_A} \sum_I X_{AS_A I} \le k \qquad \text{must have no more than "k" of the technologies}$$

$$X_{AS_A I} = X_{A'S'_{A'} I'} \qquad \text{co-requisite, i.e., technologies enable each other}$$

$$X_{AS_A I} \le X_{A'S'_{A'} I'} \qquad \text{pre-requisite, i.e., one technology enables another}$$

– Performance requirement

$$p_0 + \sum_A \sum_{S_A} p_{AS_A} \sum_I X_{AS_A I} + \sum_A \sum_{S_A} \sum_{A'} \sum_{S'_{A'}} p_{AS_A A'S'_{A'}} \sum_I \sum_{I'} X_{AS_A I} X_{A'S'_{A'} I'} + \sum_A \sum_{S_A} p_{AS_A AS_A} \sum_I X^2_{AS_A I} \ge \text{Performance Threshold}$$

– Cost upper bound

$$c_0 + \sum_A \sum_{S_A} c_{AS_A} \sum_I X_{AS_A I} + \sum_A \sum_{S_A} \sum_{A'} \sum_{S'_{A'}} c_{AS_A A'S'_{A'}} \sum_I \sum_{I'} X_{AS_A I} X_{A'S'_{A'} I'} + \sum_A \sum_{S_A} c_{AS_A AS_A} \sum_I X^2_{AS_A I} \le \text{Cost Upper Bound}$$

– Weight upper bound

$$w_0 + \sum_A \sum_{S_A} w_{AS_A} \sum_I X_{AS_A I} + \sum_A \sum_{S_A} \sum_{A'} \sum_{S'_{A'}} w_{AS_A A'S'_{A'}} \sum_I \sum_{I'} X_{AS_A I} X_{A'S'_{A'} I'} + \sum_A \sum_{S_A} w_{AS_A AS_A} \sum_I X^2_{AS_A I} \le \text{Weight Upper Bound}$$

As formulated, the MCMP is a nonlinear, 0-1 integer mathematical program. Since the non-linearities were due to the quadratic form of the objective functions and bound constraints, they could be readily removed for a 0-1 variable problem. The squared terms were linarized by simply dropping their superscripts because raising a 0 or 1 to the second power has no effect. The cross-product terms were linarized by substituting

$$X_{AS_A A'S'_{A'}} = X_{AS_A} X_{A'S'_{A'}}$$

and adding the constraints:

$$-X_{AS_A} - X_{A'S'_{A'}} + 2X_{AS_A A'S'_{A'}} \leq 0$$

$$X_{AS_A} + X_{A'S'_{A'}} - X_{AS_A A'S'_{A'}} \leq 1$$

The linearized 0-1 MCMP model was then solved iteratively to generate an efficient frontier using the constraint method. The basic concept of the constraint method is to optimize one of the objectives while treating the others as constraints whose right-hand side values are fixed at a particular level at each iteration.

The solution process was begun by solving the MCMP one objective at a time to find the minimum and maximum cost and weight solutions without regard to performance. Four mathematical programs were solved:

1. Minimize Linearized Cost Response Surface
   S.T. Feasible Technology Combinations
2. Maximize Linearized Cost Response Surface
   S.T. Feasible Technology Combinations
3. Minimize Linearized Weight Response Surface
   S.T. Feasible Technology Combinations
4. Maximize Linearized Weight Response Surface
   S.T. Feasible Technology Combinations

The solutions to these individual mathematical programs provided upper and lower bounds for cost and weight. These cost and weight ranges were then divided into *n* and *m* equal regions, respectively. This partitioned the cost-weight plane into *n* x *m* cells as shown in figure 9.

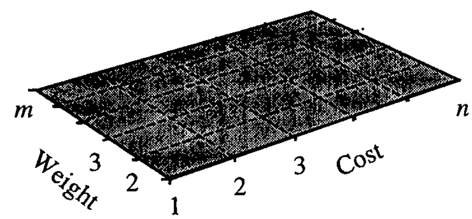


Figure 9. *The Weight-Cost Plan was Partitioned into n x m Equal Sized Cells.*

The MCMP model was then reduced to a single objective function mathematical program used to maximize performance in each of the *n* x *m* cost-weight cells. This required solution of *n* x *m* single objective mathematical programs of the form:

Maximize Linearized Performance Response Surface

S.T. Feasible Technology Combinations

$C_i \leq$ Linearized Cost Response Surface $\leq C_{i+1}$

$W_j \leq$ Linearized Weight Response Surface $\leq W_{j+1}$

Performance Requirements

Bounds

where C = Cost, W = Weight, and the indices i and j run from 1 to *n*-1 and 1 to *m*-1, respectively.

The result of the solution of each of the *n* x *m* mathematical programs is a combination of technology options that maximize performance within the cost/weight constraints of the *n* x *m* cells of the cost-weight plane. This provided a set of solutions that were used to form an approximation of the efficient frontier of non-dominated solutions as shown in figure 10.

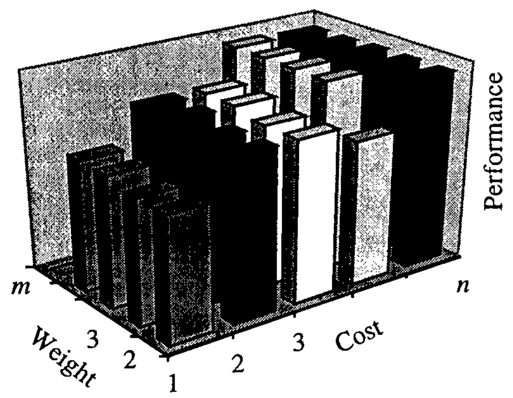


Figure 10. *A Full Set of n x m Optimum Performance Solutions was Generated.*

The set of unique solutions generated in this manner were plotted on the two dimensional plot shown in figure 11 to identify a non-dominated set of alternatives. The set of non-dominated solutions was representative of the efficient frontier of real trade-offs among attractive solutions. Figure 11 is an actual AAAV program result for the SWA scenario. The non-dominated configurations are highlighted in red.

Selected alternatives from the set of non-dominated solutions were then subjected to detailed analyses in CASFOREM and the cost and weight models to validate the results of the response surface outputs.

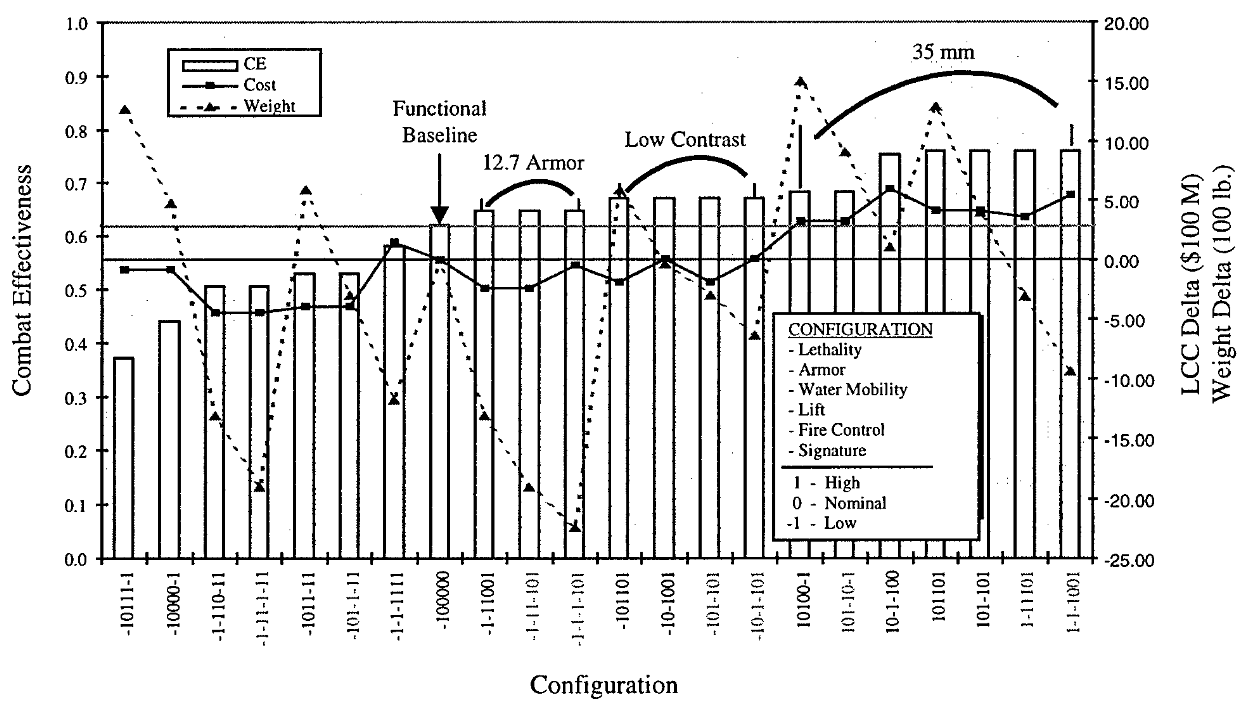
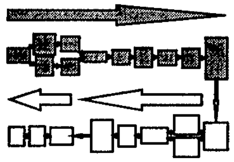


Figure 11. *A Full Set of AAAV SWA Optimum Solutions with Non-Dominated Configurations Highlighted in Red.*



The set of non-dominated candidates generated by the MCMP were then evaluated with a MCDA model to select the "best" combinations(s) of specific capability levels within each of the core capabilities. The goals hierarchy for the whole system level trades shown in figure 6 was the model used for the selection. This goals hierarchy included cost, performance (combat effectiveness) and weight considerations. A group of SMEs assessed the relative importance weights of the three selection criteria to be equal and the SUFs were taken as linear defaults. Figure 12 is the goals hierarchy trade study model used for this selection.

The results of the decision analysis are shown in figure 13. The levels of technology selected for each specific capability within the five core capability areas are highlighted in red.

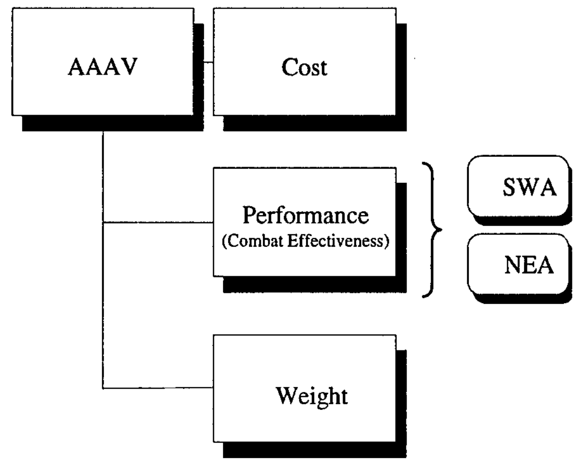


Figure 12. *The Selection Model Goals Hierarchy Considered Cost, Combat Effectiveness, and Weight Criteria as Equally Important.*

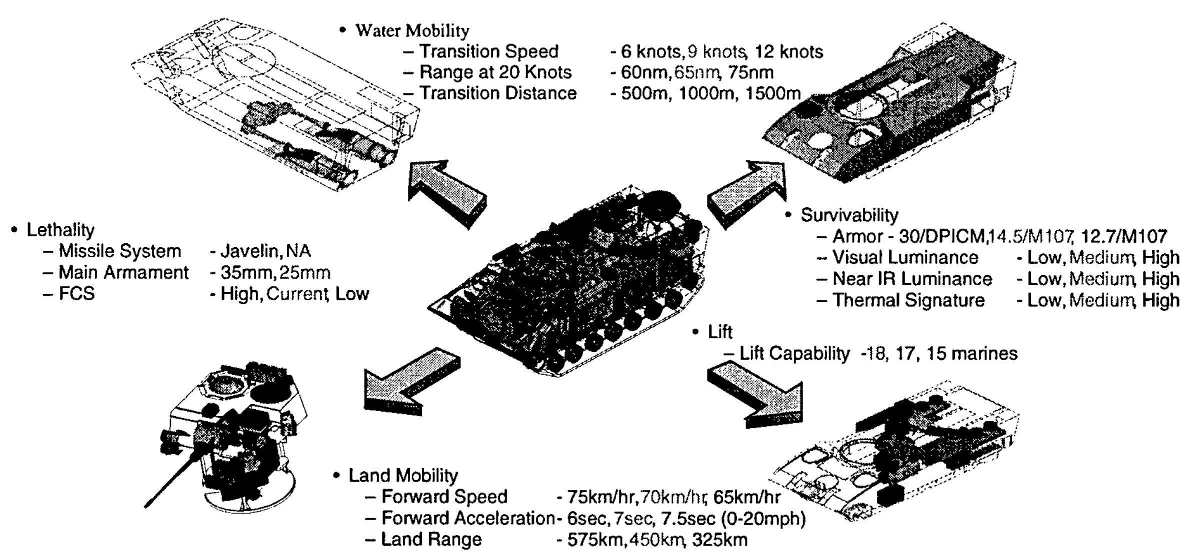
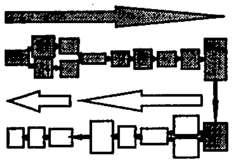


Figure 13. *The "Best" AAAV is Defined By the Specific Capability Levels Highlighted in Red.*

(2) Subsystem/Component Level Trades:



Subsystem/component level trades were next conducted for each specific capability level selected in the whole system level trades. Each specific capability level selected pointed the direction toward further expansion/focus of the technology search and selection criteria with respect to that specific capability.

Ninety-five subsystem/component level trade studies were performed. Figure 14 shows the magnitude of the trade study tree. Trade studies were assigned to IPTs according to IPT core capability area.

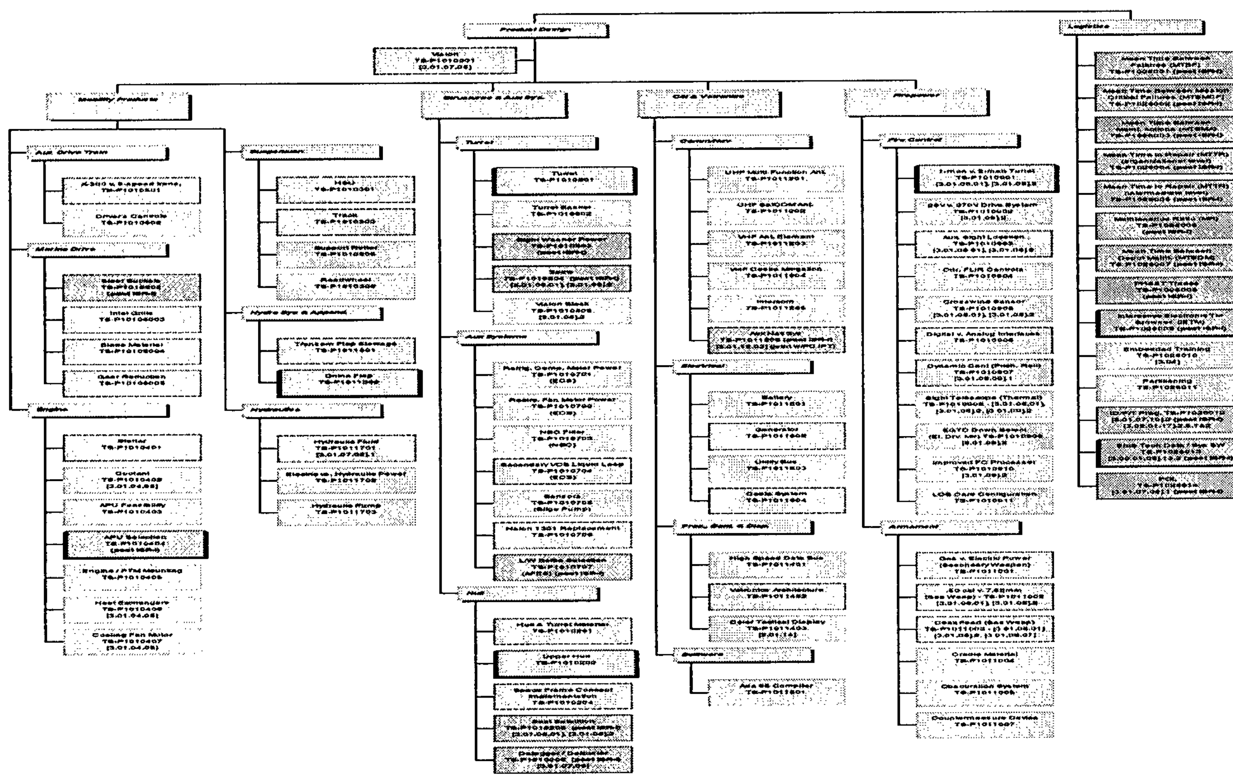


Figure 14. *The AAAV Subsystem Level IPT Trade Study Tree Contained 95 Trade Studies.*

A common starting point was provided to the IPTs in order to ensure consistency in the conduct of the individual trade studies. This common starting point consisted of training in the AAAV standard trade study process, identification of key criteria to be considered in all trade studies, a set of common SUFs for selected criteria to be used in all trade studies, and a SUF level to be assumed for all threshold considerations.

Figure 15 shows the common structure, relative importance weights, and SUF guidance provided to the IPTs. Each IPT expanded the "performance" criterion according to its own needs.

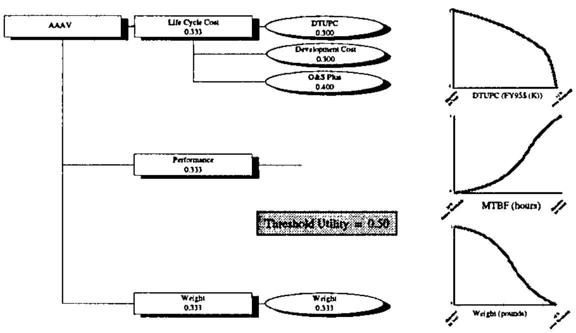


Figure 15. *Common Structure, Relative Importance Weights, and SUFs used in all Subsystem/Component Level Trade Studies.*

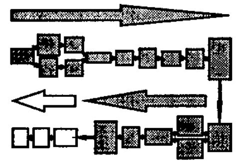


Figure 16 is an example of a specific trade study done for the AAAV weapon station. The issue to be resolved was whether the weapon station should have one or two crew members. The Firepower IPT followed the standard AAAV trade study process outlined in figure 3 above. The four tasks of the standard process were: Structure, Describe, Clarify, and Assess.

Structure the Goals Hierarchy–

A group of SMEs composed of a cross section of IPTs with customer representation expanded the "performance" goal of the common goals hierarchy to consider those aspects of performance that were pertinent to the crew size decision.

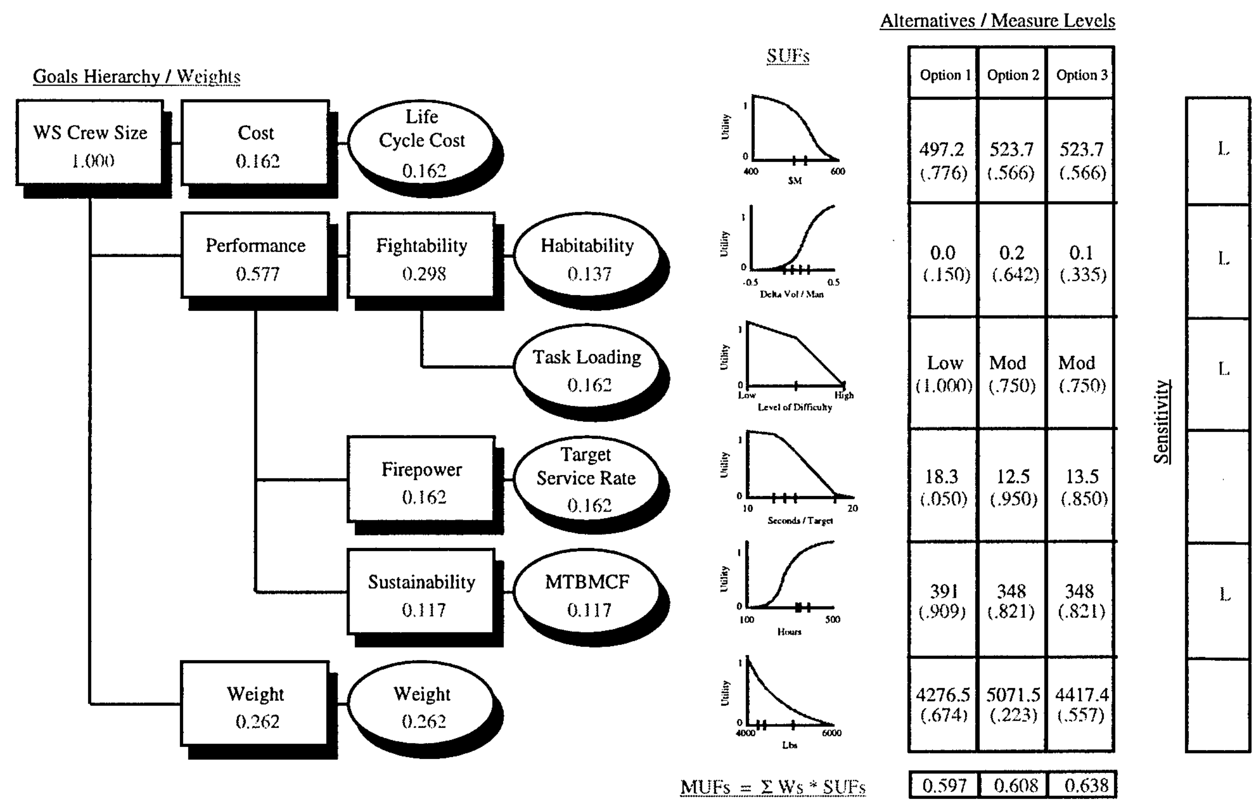


Figure 16. *The Firepower IPT Conducted a Weapon Station Crew Size Trade Study.*

The prime assumptions related to: conditions under which various measures would be taken, reduction of the size of the goals hierarchy by aggregation of several measures into one or a few proxy measures, and whether or not specific measures provided meaningful differentiation among alternatives.

- Assumptions:
  - Task Loading was sufficiently assessed under combat mode conditions.
  - Target Service Rate against the prime ground and air targets was a good proxy measure for Firepower.
  - The alternatives did not differ appreciably in Survivability or MTTR.

The result was the complete goals hierarchy in figure 16.

The Firepower IPT then developed alternative solutions. The three alternatives solutions were:

Alternative	Option 1	Option 2	Option 3
Crew Size	1	2	2
Configuration	Weapon Station	Bustle Station	Floor Ammo Can

Describe the Alternatives –

The Firepower IPT next evaluated each of the weapon station solution alternatives vis-à-vis the measures at the bottom of the goals hierarchy. Several models and analysis tools were used for this purpose. The 95 subsystem/compoent level trade studies that were performed for AAAV used multiple models and analysis tools from the entire gamut of operations research and engineering methodologies to describe the alternatives according to the measures of each trade study. Figure 17 shows the different tools that were used. Only a small number of these models were needed for the weapon station crew size study. The results of these individual analyses are the blue numbers in the columns on the right hand side of figure 16.

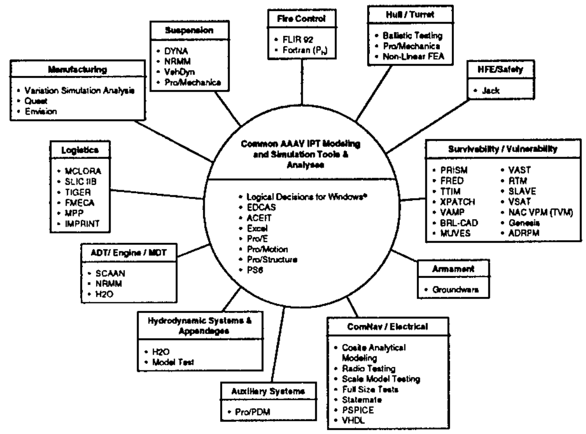


Figure 17. *Multiple Models and Analysis Tools were used for Subsystem/Component Level Trades.*

Clarify Preferences –

Preference data were elicited from the SMEs during the course of several decision conferences. Relative importance weights were elicited using the Rank Order Centroid (Smarter) method. SUFs were elicited using the three different techniques of the standard AAAV trade study process as appropriate for the particular measures:

- Habitability, and MTBMCF - MLS
- Task Loading - Adjusted AHP
- Target Service Rate - Standard Forms

The common SUFs in figure 15 were used for LCC and Weight. The results are shown in figure 16.

Assess the Alternatives –

Synthesis was performed using the additive MUF. The results in figure 18 show that Option 3, a 2 crew man option, was the preferred alternative.

Sensitivity analyses were conducted to determine whether small changes in the

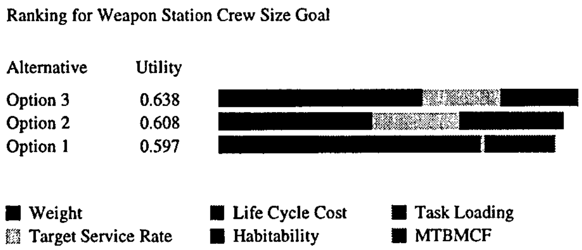


Figure 18. *Option 3 is the Preferred Alternative.*

relative importance weights of the measures would affect the ranking of the alternatives.

Figure 19 shows that the alternative ranking was insensitive to the relative importance weights of LCC, Habitability, Task Loading, and MTBMCF. For each of these measures, the relative importance weights would have to change at least 50% to affect a change in the alternative ranking.

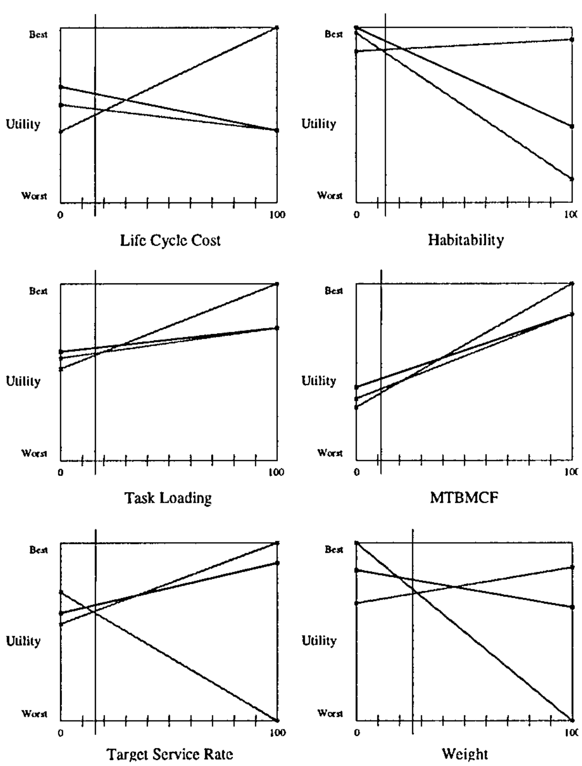


Figure 19. *Sensitivity Analyses Showed that the Ranking of Alternatives was Robust.*

The alternative ranking was, however, slightly sensitive to the relative importance weights of Target Service Rate and Weight. If Target Service Rate relative importance dropped by 29% to .12, option 1 becomes preferred. If Weight relative importance dropped by 24% to .20, option 2 becomes preferred. Decreases in relative importance weights of this magnitude for these measures were considered moderately sensitive, but unlikely. The ranking of alternatives was, therefore, considered robust.

Comparative analyses of the alternative solutions were conducted to determine the dominant measure(s) that led to this result.

- Option 3 versus Option 1.

Figure 20 shows the comparative analysis of Option 3 versus Option 1.

- Target Service Rate of 13.5 sec/kill was greatly preferred to 18.3 sec/kill.
- Habitability of 0.1 ft^3/man was only slightly preferred 0.0 ft^3/man.
- Task Loading, LCC, and Weight of option 1 are only slightly preferred.
- MTBMCF was almost equally preferred.

The dominant criterion in the preference of Option 3 over Option 1 was Target Service Rate.

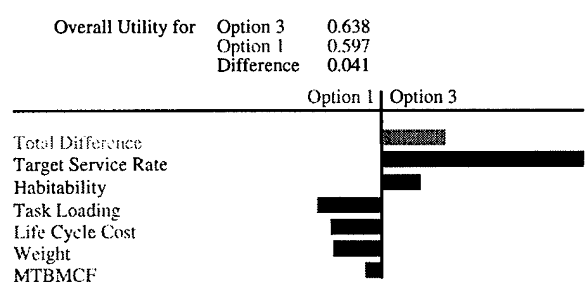


Figure 20. *Target Service Rate is the Dominant Criterion in Preference of Option 3 vs Option 1.*

- Option 3 versus Option 2.

Figure 21 shows the comparative analysis of Option 3 versus Option 1.

- Weight was the most important measure and 4417.4 lbs was much preferred to 5071.4 lbs.
- Habitability of 0.1 ft^3/man was much less preferred than 0.2 ft^3/man, but relatively unimportant with respect to Weight.
- Target Service Rate of 13.5 and 12.5 had close preference values but low importance relative to Weight.
- LCC, Task Loading, and MTBMCF were all equally preferred.

The dominant criterion in the preference of Option 3 over Option 2 was Weight.

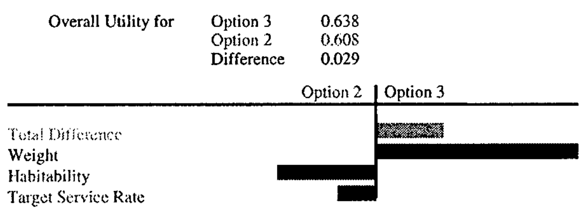
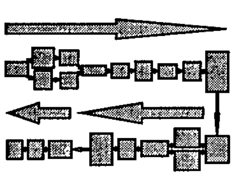


Figure 21. *Weight is the Dominant Criterion in Preference of Option 3 vs Option 2.*

(3) Concept Selection



The final set of trade studies were conducted to select the "best" AAAV concept for detailed design. The top ranked two or three non-dominated AAAV candidates, now defined by real technologies, were carried forward from the subsystem/component level trades for down select to the final preferred concept using the MCDA model shown in figure 22. This goals hierarchy has the same fundamental criteria of cost, performance, and weight as the common structure used by each IPT for the their individual subsystem/component trades. The performance fundamental criterion, however, was now subdivided into sub-goals corresponding to each of the five core capability areas with the addition of C^4I and Supportability sub-goals. Further breakdowns of these sub-goals down to the measure level corresponded to the expansion of the performance fundamental criterion that each IPT developed during their individual subsystem/component trade studies.

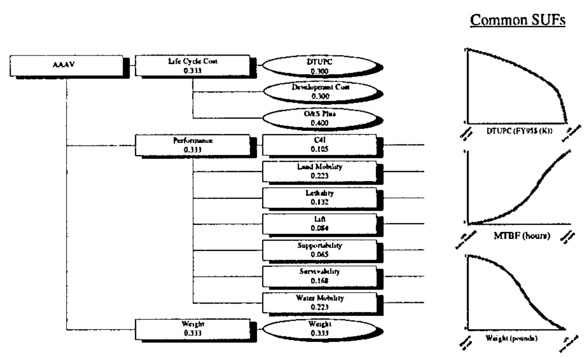


Figure 22. *The MCDA Model for Concept Selection was an Aggregate of Individual IPT Subsystem/Component Models.*

Summary and Lessons Learned

Integrated trade studies via the application of MCDA were the catalyst for the AAAV Dem/Val program systems engineering process. Three levels of trade studies were performed: (1) whole system trades, (2) subsystem/component trades, and (3) concept selection trades. Whole system trades determined the "best" balance of AAAV "core capability" performance requirements, cost, and weight. Subsystem/component level trades selected specific technologies to meet the performance requirements defined for each "core capability" in the whole system trades. Concept selection trades were used to select

the "best" AAAV alternatives(s).

Whole system trades began with a mission area analysis that included definition of threat, user/source requirements, and operational & organizational concept(s). Low, moderate, and high target performance levels were then identified for system "core capabilities". Using a DOE approach, functional relationships between the "core capability" target performance level requirements and combat effectiveness, cost, and weight were developed for use in a MCMP model. The MCMP model was used to generate a set of non-dominated candidates that were then evaluated using MCDA to select the "best" alternative(s) as defined by "core capability" performance levels.

Subsystem/component trades were conducted based on the "core capability" performance level requirements selected in the whole system trades. Each "core capability's" level helped further expand/focus its technology search and evaluation criteria.

The set of candidates, now defined by real technologies, was then evaluated using MCDA to select the "best" AAAV alternative(s).

This paper described the MCDA process used for the AAAV whole system, subsystem/component, and concept selection trades.

The success of the AAAV trade study process can be directly attributed to the following critical items:

- Management Support

  All levels of contractor and government management fully embraced the concept of using MCDA as the basis for the AAAV trade studies. Without this top level support, MCDA is a hard sell.

- Organization

  The IPT structure by core capability areas enabled control of focused subsystem/component trade studies driven by the whole system trade study results.

- Communications

  All participants must be fully aware of the activities and results of each trade study.

- Customer/User Participation

  MCDA requires a lot of judgmental data. The credibility of these data and the ability to sell the trade study results to management are critically dependent upon having the right groups of SMEs.

- Documented Process

  Formulating a standard process for the AAAV trade studies assured consistency of all trade study results. The process was documented with examples of specific techniques for eliciting relative importance weights and SUFs in a browser type document was available to all engineers though an intranet capability.

- Training

  Two-thirds of the engineering staff, both contractor and government personnel, attended a 3 day workshop on the trade study process. The workshop provided hands on experience in the use of specific techniques for eliciting relative importance weights and SUFs. The documentation referred to above served as reinforcement and a ready reference for when trade studies were actually being performed.

- Diligence

  Conducting trade studies via MCDA is not an easy process. Many frustrations arise during the SME elicitation decision conferences and in presenting results to management. Maintaining objectivity and commitment to the process was essential to the AAAV success.

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Descriptors

1. Design of Experiments
2. Mathematical Programming
3. Multiple Criteria Decision analysis
4. Response Surface Analysis
5. Systems Engineering
6. Trade studies

Acronyms

1. AAAV - Advanced Amphibious Assault Vehicle
2. ACEIT - Automated Cost Estimator
3. AHP - Analytic Hierarchy Process
4. CASTFOREM - Combined Arms and Support Task Force Evaluation Model
5. Dem/Val - Demonstration/Validation
6. DOE - Design of Experiments
7. IPT Integrated Product Team
8. LCAC - Landing Craft Air Cushion
9. MCDA - Multiple Criteria Decision Analysis
10. MCMP - Multi Criteria Mathematical Programming
11. MLS - Mid-Level Splitting
12. MOE - Measure of Effectiveness
13. MUF - Multi-measure Utility Function
14. MV-22 - Osprey Tilt-Rotor Aircraft
15. NEA - Northeast Asia
16. OMFTS - Operational Maneuver From The Sea
17. ROC - Rank Order Centroid
18. SF - Standard Forms
19. SME - Subject Matter Expert
20. STOM - Ship To Objective Maneuver
21. SUF - Single-measure Utility Function
22. SW - Swing Weights
23. SWA - Southwest Asia

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14. ABSTRACT

Multiple Criteria Decision Analysis (MCDA) was an integral part of concept definition for the Marine Corps AAAV program. Three levels of trade studies were performed: (1) whole system trades, (2) subsystem/component trades, and (3) concept selection trades. Whole system trades determined the "best" balance of AAAV "core capability" performance requirements, cost, and weight. Subsystem/component level trades selected specific technologies to meet the performance requirements defined for each "core capability" in the whole system trades. Concept selection trades were used to select the "best" AAAV alternatives(s).

This paper describes the analysis process used for the AAAV whole system, subsystem/component, and concept selection trades.

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